Risk assessment of root resorption using computed tomography values and computed texture analysis
（CT 値と CT Texture 解析による歯根吸収のリスク評価）

日本大学大学院松戸歯学研究科
歯科矯正学
金尾　茉優

（指導：根岸　慎一　教授）

本論文は

1)   Association of computed tomography values of the tooth root and alveolar bone with orthodontic root resorption

International Journal of Oral-Medical Science, 2023, March, in press

2) Risk assessment of external apical root resorption associated with orthodontic treatment using computed tomography texture analysis

https://doi.org/10.1007/s11282-022-00604-3, Oral Radiography, 2022, March 18th
をまとめたものである。

1. Abstract

【Introduction】

Study 1 aimed to quantitatively evaluate computed tomography (CT) images of maxillary central incisor roots taken before orthodontic treatment by using CT Texture analysis. In Study 2, the effect of CT values of maxillary central incisor roots and alveolar bone on root resorption were evaluated using data before and after orthodontic treatment.

【Materials and Methods】

<Study 1>

Thirty-two patients with jaw deformities were divided into those with and without root resorption (male = 16, female = 16). Texture features of the maxillary central incisor with and without root resorption after orthodontic treatment were analyzed using the open-access software, MaZda Ver. 3.3. Ten texture features (4 of GLRLM, 6 of GLCM) were selected using the Fisher method in MaZda from 279 original parameters, which were calculated for each maxillary central incisor with and without root resorption. GLRLM provides the length of homogeneous runs for each gray level in four directions. GLCM considers the spatial relationship of pixels and indicates the frequency of pixel pairs within a distance of five pixels around the pixel of interest.

<Study 2>

Forty-one patients with jaw deformities were divided into those with and without root resorption (male = 18, female = 23). The distance from the anatomical root apex to the edge of the incisive canal was measured using axial CT sections before active treatment. The distance from the anatomical root apex to the labial and palatal cortical bone and the CT values of the root and alveolar bone were measured and compared using

sagittal CT sections. The tooth axis and vertical and lateral movements of the maxillary central incisor were examined before and after treatment using lateral cephalograms.

【Results】

<Study 1>

Four gray level run length matrix (GLRLM) features and six gray level co-occurrence matrix (GLCM) features displayed significant differences between both groups ($p<0.01$).

<Study 2>

The root resorption group showed significantly higher CT values of alveolar bone than the control group ($p<0.05$), different axial movement of the root apex ($p<0.05$), and the distance between the labial cortical bone and root apex on lateral cephalograms ($p<0.05$).

【Conclusion】

・Homogeneous root structure is associated with root resorption.

・A greater horizontal movement of the root apex is associated with a greater risk of root resorption.

・A shorter distance between the root apex and the labial cortical bone is associated with a greater risk of root resorption.

・Higher CT values of the alveolar bone around the tooth root were associated with a greater risk of tooth root resorption.

・CT imaging before orthodontic treatment may enable safer treatment.

Keywords: Root resorption, Computed tomography value, Lateral cephalogram, Multidetector-row computed tomography, Texture analysis

2. Introduction

Orthodontic treatment aims to improve the aesthetics of protruding teeth, plexus, oppositional bite, and mandibular function (1). However, it also has disadvantages, such as extended treatment time and significant mental stress that patients undergo from wearing an oral appliance (2). Tooth movement may also lead to gingival recessions (3) and root resorption (4), which vary between patients. Risk factors that contribute to root resorption can be divided into several categories: those related to orthodontic treatment, such as the length of treatment (5), tooth movement type (6), and excessive orthodontic force (7) and those related to individuals, including genetics (8), age (9), root morphology (10), dental trauma (11), and allergies (12). Kaley and Phillips (13) reported that root resorption often occurred after orthodontic treatment, and severe root resorption exceeding one-quarter of the root length was observed in 3% of axillary central incisors. Furthermore, a root resorption of 2 mm or more is considered clinically important such as affecting long-term stability after treatment (14).

Imaging is essential to confirm the presence and severity of root resorption; however, all previous studies assessed risk factors for root resorption qualitatively, not quantitatively, using pre-orthodontic imaging. In recent years, radiomics, which comprehensively analyses biological information in association with quantitative features extracted from medical images, has been employed in various medical fields (15-17). Texture analysis is a commonly used radiomics technique used for quantifying images (18) that can identify spatial pixel patterns and quantify textures in images that the human eye cannot discern. Although there have been a few studies using Texture analysis in dentistry, there have been no studies using Texture analysis in orthodontic treatment.

On the other hand, Tooth hardness and alveolar bone are also considered implicating factors. Yao-Umezawa et al. (19) reported a positive correlation between cementum hardness and root resorption in rat experiments. However, the effect of tooth microstructure and alveolar bone hardness on root resorption has not yet been elucidated. Sameshima and Sinclair (20) found that root resorption was twice as likely to occur in maxillary central incisors than in mandibular central incisors. Yagci et al. (21) reported that the contact of the maxillary central incisor roots with hard tissue structures, such as incisive canals and cortical bone, was a significant risk factor for root resorption. In addition, Baba et al. (22) reported that computed tomography (CT) values and bone mineral density (BMD) are positively correlated. However, there have been no reports regarding the use of CT values to observe root resorption and alveolar bone pre- and post-treatment and alveolar bone changes.

The purposes of this study are

< Study 1> The roots of maxillary central incisors were quantitatively evaluated by Texture analysis using data obtained before and after orthodontic treatment, and the association between the roots and root resorption was examined.

<Study 2> The lateral cephalograms taken before and after orthodontic treatment were used to evaluate tooth movement patterns, and CT was used to examine the association between the maxillary central incisors and their surrounding anatomical structures and the roots and alveolar bone.

3. Materials and Methods

Research participants

<Study 1>

Thirty-two patients with jaw deformities who underwent CT (Aquilion 64; Toshiba Medical Systems, Tokyo, Japan) between 2006 and 2016 were enrolled in this study. The patients were divided into two groups: 16 patients in the root resorption group (male = 4, female = 12; mean age: 22.8 years; range, 16–34 years) and 16 patients in the control group (male = 4, female = 12; mean age: 22.8 years; range, 16–34 years) (Table 1).

<Study 2>

Forty-one patients with jaw deformities who underwent CT (Aquilion 64; Toshiba Medical Systems, Tokyo, Japan) between 2010 and 2019 were enrolled in this study. The patients were divided into two groups: 18 patients in the root resorption group (male = 4, mean age: 20 ± 2 years; female = 14, mean age: 25 ± 6 years) and 23 patients in the control group (male = 10, mean age: 19 ± 2 years; female = 13, mean age: 23 ± 4 years) (Table 2).

As a common baseline for both studies, the patients had undergone CT and lateral cephalometric imaging before and after active treatment. All patients had Roth-type preadjusted brackets with 0.022 x 0.028-inch slots, using 0.019 x 0.025-inch stainless steel wire as the final wire and had no difference in the mean duration of treatment. Patients with a history of orthodontic treatment, systemic diseases or allergies, and trauma or endodontic treatment of the maxillary right central incisor were excluded from the studies.

The sagittal CT sections of the patients before and after active treatment of the root of the maxillary right central incisor were compared, and the classification proposed by Malmgren et al. (11) was applied. Grade 3 (one-third of the original length) or higher indicated root resorption (Fig. 1). The presence or absence of root resorption was evaluated by a radiologist (K.I., with 11 years of experience) and an orthodontist (M.K., with 4 years of experience). These studies were approved by the Ethics Committee of Nihon University School of Dentistry at Matsudo (approval number: EC 20-008). Written informed consent was obtained from all participants, a copy of which is available for review upon request. Blinding was not applied to the study design.

Imaging protocols (Study 1,2)

The CT imaging parameters used were: tube voltage, 120 kV; tube current, 100 mA; field of view, 240 x 240 mm; helical pitch, 41; rotation time, 1.0 s; and reconstruction slice thickness, 0.5 mm. Sagittal CT sections were used to compare and measure the root of the maxillary right central incisor before and after active treatment. CT images were interpreted using a medical liquid-crystal display monitor (RadiForce G31; Eizo Nanao, Ishikawa, Japan).

Image Analysis and Assessment (Study 1)

Texture features of patients with and without root resorption were analyzed using the open-access software, MaZda Ver. 3.3 (Technical University of Lodz, Institute of Electronics, Poland) (23-25). Histogram, absolute gradient GLRLM, GLCM, and autoregressive model were selected in MaZda feature extraction setting, and 279 texture features were extracted from each region of interest (ROI) on CT in Digital Imaging and Communications in Medicine format (Fig. 2) (26).

These texture features are described on the software package website (http://www.eletel.p.lodz.pl/programy/mazda). Ten texture features with the largest Fisher coefficients were selected using the Fisher method in MaZda for automatic feature selection from the 279 original parameters.

Maxillary superimposition (Study 2)

The maxillary right central incisor identified in the pre-treatment cephalometric image of each patient was traced along with the incisor in the post-treatment cephalometric image, which was aligned with the tooth axis. The positions of the anterior nasal spine (ANS) and posterior nasal spine (PNS) were confirmed using the lateral cephalogram, and the palatal plane was traced by connecting these points.

Two vertical tooth movements were measured for each film: (1) from the maxillary central incisal edge to the palatal plane (I-VRT) and (2) from the apex of the central incisor to the palatal plane (A-VRT).

Sagittal tooth movement was measured in the plane vertical to the palatal plane crossing at PNS. Two horizontal tooth distances were measured for each film: (1) the distance from the incisal edge to the plane perpendicular to the PNS (I-HRZ) and (2) the distance from the root edge to the plane perpendicular to the PNS (A-HRZ) (27).

The films before and after treatment were compared, and the distance moved by the incisal edge and root apex was calculated. In addition, the angular measurement of the incisors was determined. The posterior inferior angle formed by the intersection of the tooth axis and the palatal surface of the maxillary central incisor was measured on each film (Fig. 3).

Distance from the root apex to the incisive canal of the maxillary right central incisor (Study 2)

The shortest distance from the anatomical root apex of the maxillary central incisor to the incisive canal margin was measured using transverse sections of CT images (Fig. 4) (28).

Distance from the root apex to the labial/palatal cortical bone (Study 2)

The distance from the root apex to the labial/palatal cortical bone was measured using the plane of vertical intersection of the tooth axis and the anatomical root apex (Fig. 5).

Determination of the CT value of the root (Study 2)

The CT value of the root was determined as the average of the CT values of four regions of interest (ROI) in the apical third of the tooth, including two in the coronal section (mesial and distal) and two in the sagittal section (labial and palatal), encompassing as large an area as possible without affecting the images corresponding to the periodontal ligament and pulp. The ROI in each section had the same dimensions (Fig. 6) (29).

Determination of the CT value of the alveolar bone

The CT values of the alveolar bone were measured from the same sagittal section used for the CT value of the root. The CT value of the alveolar bone was determined as the average of the CT values of four ROI in the alveolar bone: three 1 x 1mm regions located on the palatal side in the apical third of the root and a 1 x 2mm region located above the root apex (Fig. 7) (29). The researchers performing the measurements were not blinded to the participant's group allocation.

Statistical analysis

<Study 1>

Patient characteristics and texture parameters were compared between patients with and without root resorption. Results for continuous variables are presented as mean ± standard deviation. After performing the Shapiro-Wilk test and F-test for continuous variables, where appropriate, the Student's t-test, Welch's t-test, or Mann-Whitney U test was used to assess for differences in continuous variables based on patient characteristics and texture parameters. As for categorical variables, frequencies were presented as the number of patients (column percentage). Fisher's exact test was used to examine differences in categorical variables according to patient characteristics.

<Study 2>

Statistical analysis was performed using the Statistical Package for Social Sciences (version 28.0.0; IBM, Armonk, NY). All measurements were performed according to the normality of the distribution of variables, which was statistically evaluated using the Student's t-test after performing the Shapiro-Wilk test and F-test for continuous variables. Statistical significance was established at $p < 0.05$. A discriminant function using cephalogram and CT recordings was produced based on 10 variables, and this function was considered statistically significant at $p < 0.001$.

4. Results

<Study 1>

Table 3 shows texture features of roots with and without root resorption after orthodontic treatment using the Student's t-test, Welch's t-test, and Mann-Whitney U test. Four GLRLM features (horizontal-short-run emphasis [SRE], horizontal-Fraction, horizontal-long-run emphasis [LRE], and vertical-Fraction) and six GLCM features (S(1,0) inverse difference moment [IDM], S(0,1) angular second moment [ASM], S(0,2) ASM, S(1,0) ASM, S(0,1) entropy, and S(1,0) entropy) showed significant differences between patients with and without root resorption after orthodontic treatment ($p<0.01$). Post-hoc power analysis showed that the power between the two groups was 0.933 for horizontal-SRE, 0.879 for horizontal-LRE, 0.910 for horizontal-Fraction, 0.910 for vertical-Fraction, 0.917 for S(1,0) IDM, 0.875 for S(0,1) ASM, 0.889 for S(0,2) ASM, 0.933 for S(1,0) ASM, 0.863 for S(0,1) entropy, and 0.863 for S(1,0) entropy.

<Study 2>

Cephalometric measurement results

The differences before and after orthodontic treatment were calculated for all parameters and compared between root resorption and control groups, with significant differences determined using the Student's t-test. A significant difference was observed only in A-HRZ, and there was no significant difference in other parameters, including tooth axis, A-VRT, I-HRZ, and I-VRT (Table 4).

CT measurement results

A significant difference between the groups was found only in the distance between the labial cortical bone and maxillary central incisor (Table 5). The distance between the incisive canal and maxillary central incisor and between the palatal cortical bone and maxillary central incisor was insignificant. The CT value of the root was not significantly different; however, the CT value of the alveolar bone was significantly different (Table 6).

A discriminant function based on 10 variables was obtained by discriminant analysis using the cephalogram and CT recordings (Table 7). A-HRZ was the most important factor since independent variables with large absolute values contribute to the discrimination. This function was statistically significant at $p<0.001$, and 81 per cent of the groups were correctly classified. The equation for obtaining the discriminant scores was: Discriminant score (z) = 0.927*A-HRZ + 2.534*A-VRT + 1.320*I-HRZ + -0.826*I-VRT + -0.034* distance from the incisive canal to the maxillary central incisor+ -0.004*CT value of the root + -0.003*CT value of the alveolar bone + 0.648*distance between the labial cortical bone and maxillary central incisor + 0.055*distance between the palatal cortical bone and maxillary central incisor + -0.012*inclination - 8.617.

5. Discussion

Among the 10 texture features that were selected using the Fisher method in MaZda, the right maxillary central incisor root with and without root resorption revealed significant differences in four GLRLM and six GLCM features. Moreover, the selected texture features exhibited high diagnostic performance. Thus, texture analysis using CT before orthodontic treatment may be a useful new method for predicting root resorption after orthodontic treatment.

GLRLM provides the length of homogeneous runs for each gray level in four directions. SRE represents the distribution of short gray level runs and shows a lower value if the image is highly uniform, whereas LRE represents the distribution of long gray levels and shows a higher value if the image is highly uniform (30). Fraction represents the homogeneity of the runs and will have a low value if the ROI volume is highly uniform (30, 31). In this study, the maxillary central incisor roots with root resorption had a lower SRE, higher LRE, and lower Fraction than did the maxillary central incisor roots without root resorption. Hence, the maxillary central incisor roots with root resorption show high uniformity than those without root resorption in CT images.

GLCM is a texture feature that considers the spatial relationship of pixels and indicates the frequency of pixel pairs within a distance of five pixels around the pixel of interest (30, 32). IDM represents local uniformity of the gray-level pixel pairs. When the value of the density co-occurrence matrix is concentrated on a specific element on the main diagonal, it becomes a high value, indicating that the density difference is small and there are many points with a specific density value on the image. ASM is the sum of the squares of entries, and it represents uniformity of the gray-level pixel pairs within the entire ROI. When an image has good homogeneity or the pixels are considerably similar, it becomes a high-value image. Entropy is the randomness of the gray-level pixel pairs. If entropy is low, the randomness of the pixel pairs is said to decrease. In this study, the maxillary central incisor roots with root resorption had a higher IDM, higher LRE, and lower entropy than those without root resorption. Therefore, the maxillary central incisor roots with root resorption show more local and overall uniformity than those without root resorption on CT images.

To determine the effect of CT values of the tooth root and alveolar bone on root resorption, the vertical and horizontal movements of the maxillary central incisors, the distance from the anatomical tissues surrounding the maxillary central incisor, and the CT values of the root and lingual alveolar bone of the maxillary central incisor, were examined. The correlation between root resorption and tooth movement has been reported earlier (27, 33, 34).

Firstly, the vertical and horizontal movements of the maxillary central incisors were measured from cephalogram images of all patients before and after orthodontic treatment. The movement analysis before and after orthodontic treatment indicated a significant difference between the groups in A-HRZ. The difference in the root resorption group was negative, whereas that in the control group was positive. This means that the root apex in the root resorption group moved labially, i.e., the central incisor was tipped. Secondly, CT images of all patients taken before orthodontic treatment were used to measure the distance between the maxillary central incisor and the surrounding anatomical tissues, such as the incisive canal and the labial and palatal cortical bone. The CT values of the roots and lingual alveolar bone of the maxillary central incisors were also measured. There was no significant difference in the distance between the root apex of the maxillary central incisor and the cortical bone on the palatal side in either group or the CT values of the roots. However, there was a significant difference in the distance between the labial cortical bone and maxillary central incisor and the CT values of the alveolar bone on the lingual side of the root. In the root resorption group, the distance between the labial cortical bone and the maxillary central incisor decreased compared to the control group. In the root resorption group, the CT values of the lingual alveolar bone of the roots were higher than those of the control group. These results suggest that the distance between the root apex and labial cortical bone before orthodontic treatment and the CT values of the alveolar bone are critical factors associated with apical root resorption.

However, it has been suggested that contact of the root with the cortical bone is a critical factor for root resorption in orthodontic treatment (8, 35). A study by Linares (36) showed that root resorption is more likely to occur when the bone in contact is dense, as this causes more stress on the roots than a less dense bone.

Scheibel et al. (37) reported that the anterior alveolar regions of the maxilla and mandible in humans have greater densitometric values in comparison to posterior regions and later documented that high bone density is related to higher levels of root resorption affecting the maxillary incisors (38). This may be one factor influencing root resorption of the maxillary incisors. They also found a correlation between systemic BMD and alveolar bone mass (37). Baba et al. (22) reported that CT values and BMD correlate positively. Taken together, higher CT values of the alveolar bone are associated with higher bone densities that increase the risk of tooth root resorption.

In future studies, cone-beam computed tomography (CBCT) should be used for risk diagnosis of root resorption because of its greater convenience and lower radiation exposure than multidetector row computed tomography (MDCT).

6. Conclusion

- Homogeneous root structure is associated with root resorption.
- A greater horizontal movement of the root apex is associated with a greater risk of root resorption.
- A shorter distance between the root apex and the labial cortical bone is associated with a greater risk of root resorption.
- Higher CT values of the alveolar bone around the tooth root were associated with a

greater risk of tooth root resorption.

・CT imaging before orthodontic treatment may enable safer treatment.

7. References

1) Proffit WR, Fields HW, Sarver DM: Contemporary orthodontics, 6th ed, 2019, St Louis, Mosby, USA.

2) Al-Omiri MK, Abu Alhaija ES: Factors affecting patient satisfaction after orthodontic treatment. Angle Orthod, 76: 422-431, 2006.

3) Bollen AM, Cunha-Cruz J, Bakko DW, Huang GJ, Hujeol PP: The effects of orthodontic therapy on periodontal health: a systematic review of controlled evidence. J Am Dent Assoc, 139: 413-422, 2008.

4) Smale I, Årtun J, Behbehani F, Doppel D, van't Hof M, Kuijpers-Jagtman AM: Apical root resorption 6 months after initiation of fixed orthodontic appliance therapy. Am J Orthod Dentofacial Orthop, 128: 57-67, 2005.

5) Reitan K: Initial tissue behavior during apical root resorption. Angle Orthod, 44: 68-82, 1974.

6) DeShields RW: A study of root resorption in treated class II, division I malocclusions. Angle Orthod, 39: 231-245, 1969.

7) Chan E, Darendelier MA: Physical properties of root cementum: Part 5. Volumetic analysis of root resorption craters after application of light and heavy orthodontic forces. Am J Orthod Dentofacial Orthop, 127: 186-195, 2005.

8) Al-Qawasmi RA, Hartsfield JK Jr, Everett ET, Flury L, Liu L, Foroud TM, Macri JV, Roberts WE: Genetic predisposition to external apical root resorption in orthodontic patients: linkage of chromosome-18 marker. J Dent Res, 82: 356-360, 2003.

9) Reitan K: The tissue reaction as related to the age factor. Eur J Orthod, 29: 58-64, 2007.

10) Levander E, Malmgren O, Stenback K: Apical root resorption during orthodontic treatment of patients with multiple aplasia: a study of maxillary incisors. Eur J Orthod, 20: 427-434, 1999.

11) Malmgren O, Goldson L, Hill C, Orwin A, Petrini L, Lundberg M: Root resorption after orthodontic treatment of traumatized teeth. Am J Orthod, 82: 487-491, 1982.

12) Shimizu M, Yamaguchi M, Fujita S, Utsunomiya T, Yamamoto H, Kasai K: Interleukin-17/T-helper 17 cells in an atopic dermatitis mouse model aggravate orthodontic root resorption in dental pulp. Eur J Oral Sci, 121:101-110, 2013.

13) Kaley J, Phillips C: Factors related to root resorption in edgewise practice. Angle

Orthod, 125-132, 1991.

14) Lopatiene K, Dumbravaite A: Risk factors of root resorption after orthodontic treatment. Stomatologija, 10:89-95, 2008

15) Lambin P, Rios-Velazquez E, Leijenaar R, Carvalho S, van Stiphout RG, Granton P, Zegers CM, Gillies R, Boellard R, Dekker A, Aerts HJ: Radiomics: extracting more information from medical images using advanced feature analysis. Eur J Cancer, 48: 441-446, 2012.

16) Avanzo M, Stancanello J, El Naqa I: Beyond imaging: the promise of radiomics. Phys Med, 38: 122-139, 2017.

17) Valdora F, Houssami N, Rossi F, Calabrese M, Tagliafco AS: Rapid review: radiomics and breast cancer. Breast Cancer Res Treat, 169: 217-229, 2018.

18) Mosquera-Lopez C, Agaian S, Velez-Hoyos A, Thompson I: Computer-aided prostate cancer diagnosis from digitized histopathology: a review on texture-based systems. IEEE Rev Biomed Eng, 8: 98-113, 2015.

19) Yao-Umezawa E, Yamaguchi M, Shimizu M, Kikuta J, Suzuki K, Kasai K: Relationship between root resorption and individual variation in the calcium/phosphorous ratio of cementum. Am J Orthod Dentofacial Orthop, 152: 465-470, 2017.

20) Sameshima GT, Sinclair PM: Predicting and preventing root resorption: Part II. Treatment factors. Am J Orthod Dentofacial Orthop, 119: 511-515, 2001.

21) Yagci A, Veli I, Uysal T, Ucar FI, Ozer T, Enhos S: Dehiscence and fenestration in skeletal Class I, II, and III malocclusions assessed with cone-beam computed tomography. Angle Orthod, 82: 67-74, 2012.

22) Baba S, Motomura G, Ikemura S, Yamaguchi R, Utsunomiya T, Hatanaka H, Hatanaka H, Kawano K, Xu M, Nakashima Y: Is bone mineral density lower in the necrotic lesion in pre-collapse osteonecrosis of the femoral head?. J Orthop Res, 38: 2434-242, 2020.

23) Szczypinski P, Strzelecki M, Materka A: MaZda-a software for texture analysis, In Proceedings of ISITC, Vol. 2007, 245-249, South Korea.

24) Strzelecki M, Szczypinski P, Materka A, Klepaczko A: A software tool for automatic classification and segmentation of 2D/3D medical images. Nucl Instrum Methods Phys Res A, 702: 137-140, 2013.

25) Szczypiński PM, Strzelecki M, Materka A, Klepaczko A: MaZdaA software package for image texture analysis. Comput Methods Programs Biomed, 94: 66-76, 2009.

26) Haralick RM, Shanmugam K, Dinstein I: Textural features for image classification,

IEEE Trans Syst Man Cybern, Vol. SMC-3, No. 6: 610-621, 1973, USA.

27) Parker RJ, Harris EF: Directions of orthodontic tooth movements associated with external apical root resorption of the maxillary central incisor. Am J Orthod Dentofacial Orthop, 114: 677-683, 1998.

28) Matsumura T, Ishida Y, Kawabe A, Ono T: Quantitative analysis of the relationship between maxillary incisors and the incisive canal by cone-beam computed tomography in an adult Japanese population. Prog Orthod, 18: 24, 2017.

29) Campos MJ, de Albuquerque EG, Pinto BC, Húngaro HM, Gravina MA, Fraga MR, Vitral RW: The role of orthodontic tooth movement in bone and root mineral density: a study of patients submitted and not submitted to orthodontic treatment. Med Sci Monit, 18: CR752-747, 2012.

30) Ito K, Muraoka H, Hirahara N, Sawada E, Okada S, Kaneda T: Quantitative assessment of normal submandibular glands and submandibular sialadenitis using CT texture analysis: a retrospective study. Oral Surg Oral Med Oral Pathol Oral Radiol, 132: 112-117, 2021.

31) Castellano G, Bonilha L, Li LM, Cendes F: Texture analysis of medical images. Clin Radiol, 59: 1061-1069, 2004.

32) Mohanaiah P, Sathyanarayana P, GuruKumar L: Image texture feature extraction

using GLCM approach. Int J Sci Res Pub, 3: ISSN: 2250-3153, 2013.

33) Dubic A, Giannopoulou C, Meda P, Montet X, Kiliaridis S: Orthodontically induced cervical root resorption in humans is associated with the amount of tooth movement. Eur J Ortho, 39: 534-540, 2017.

34) Ajmera S, Venkatesh S, Ganeshkar SV: Volumetric evaluation of root resorption during orthodontic treatment. J Clin Orthod, 48: 113-119, 2014.

35) Horiuchi A, Hotokezaka H, Kobayashi K: Correlation between cortical plate proximity and apical root resorption. Am J Orthod Dentofacial Orthop, 114: 311-318, 1998.

36) Iglesias-Linares A, Manford L, Hartsfiels JK Jr: Bone density and dental external apical root resorption. Curr Osteoporos Rep, 14: 292-309, 2019.

37) Scheibel PC, Ramos AL, Iwaki LCV: Is there correlation between alveolar and systemic bone density?. Dental Press J Orthod, 18: 78-83, 2013.

38) Scheibel PC, Ramos AL, Iwaki LCV, Micheletti KR: Analysis of correlation between initial alveolar bone density and apical root resorption after 12 months of orthodontic treatment without extraction. Dental Press J Orthod, 19: 97-102, 2014.

8. Figure legends

Fig. 1 Malmgren's classification

Grade 0, no resorption; Grade 1, irregularity of the root apex; Grade 2, resorption of 2 mm; Grade 3, resorption of 2 mm to one-third of the root apex; Grade 4, resorption of more than one-third of the root apex.

Fig. 2 Region of interest (ROI) placement of central incisor root on computed tomography (CT) images.

ROI were manually placed by tracing the contours of the right central incisor root on an axial slice that corresponding to one-third of the apex. The right central incisor root was segmented, excluding root canal. The CT image shows the ROI placement on the root with root resorption after orthodontic treatment (A, red region) and on the root without root resorption after orthodontic treatment (B, green region).

Fig. 3 Movement of the maxillary central incisor

Tooth axis of the maxillary central incisor (θ), vertical (I-VRT) and horizontal (I-HRZ) movement of the incisal edge, and vertical (A-VRT) and horizontal (A-HRZ) movement of the root apex. ANS: anterior nasal spine; PNS: posterior nasal spine

Fig. 4 Minimum distance from the anatomical root apex of the maxillary central incisor to the incisive canal margin

Fig. 5 Distance from the anatomical root apex perpendicular to the maxillary central incisor axis to the cortical bone on the labial and palatal sides

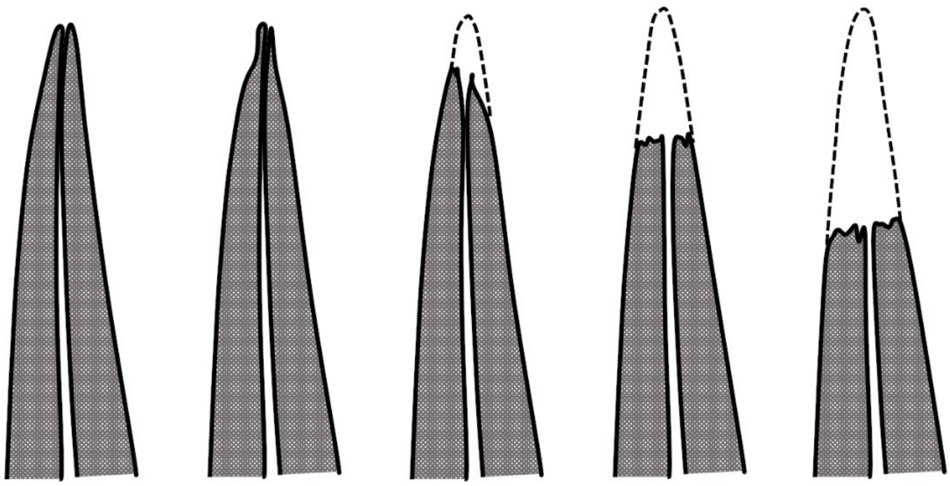
(a) Distance to the cortical bone on the labial side. (b) Distance to the cortical bone on the palate.

Fig. 6 Computed tomography (CT) value collection site (alveolar bone)

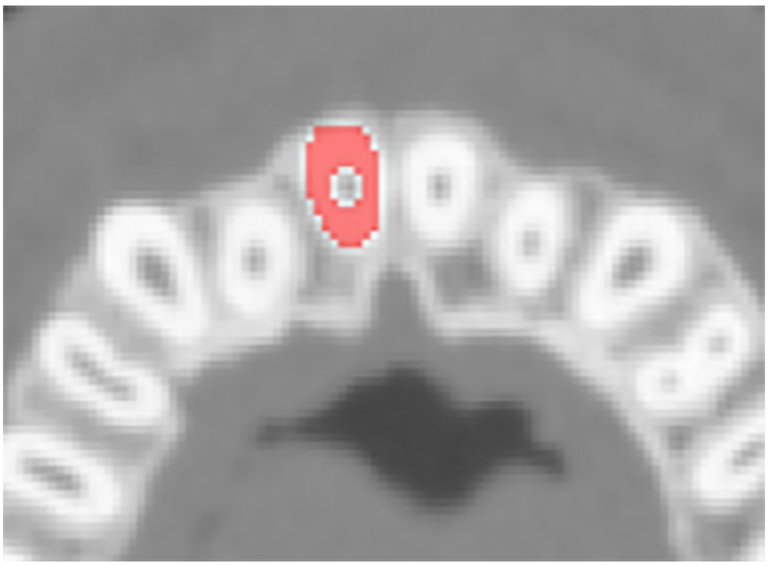
Three areas surrounding a 1 × 1-mm area on the lingual side of one-third of the root apex in the sagittal plane of the CT and a 1 × 2-mm area above the root apex.

Fig. 7 Computed tomography (CT) value collection site (root)

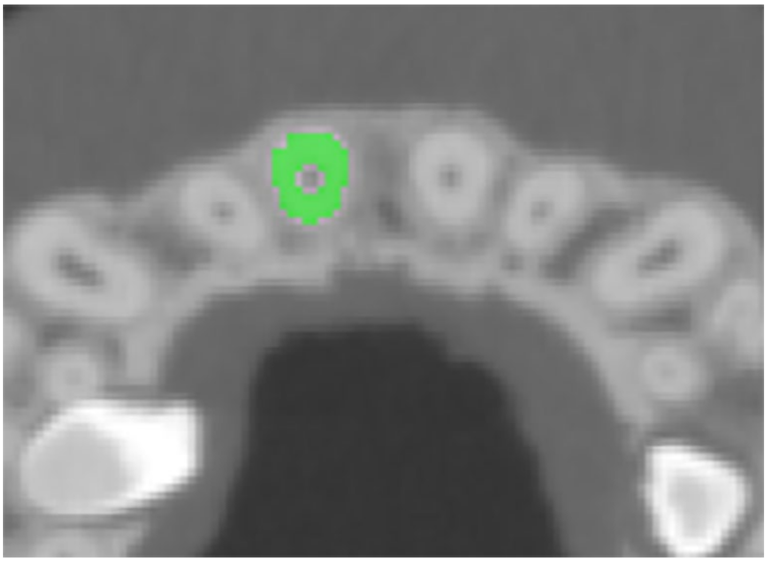
The areas at one-third of the root apex in the sagittal and coronal planes of the CT scan surrounded by the largest region of interest.



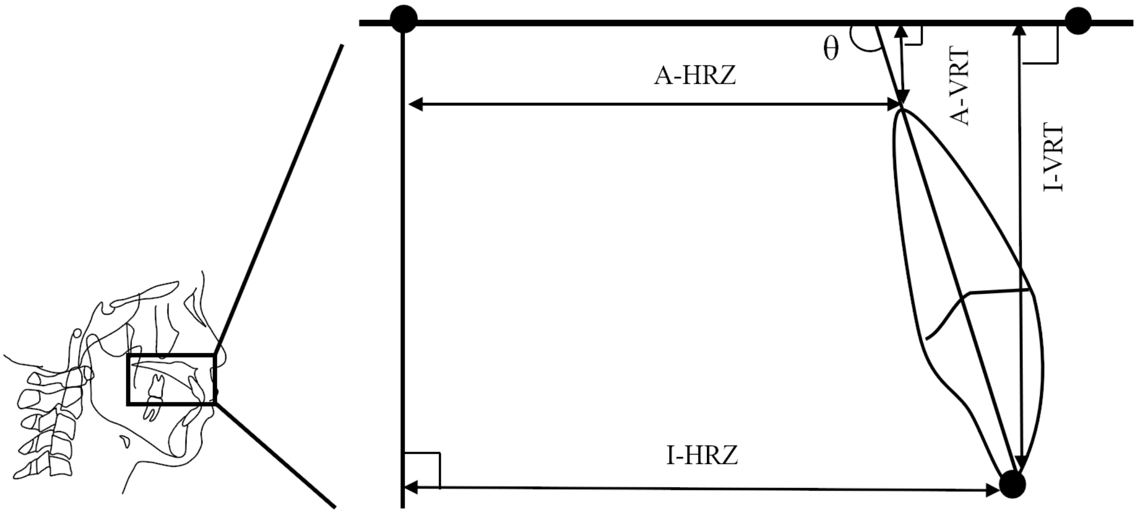
Kurasawa-Kanao et al. Fig. 1



Kurasawa-Kanao et al. Fig. 2A

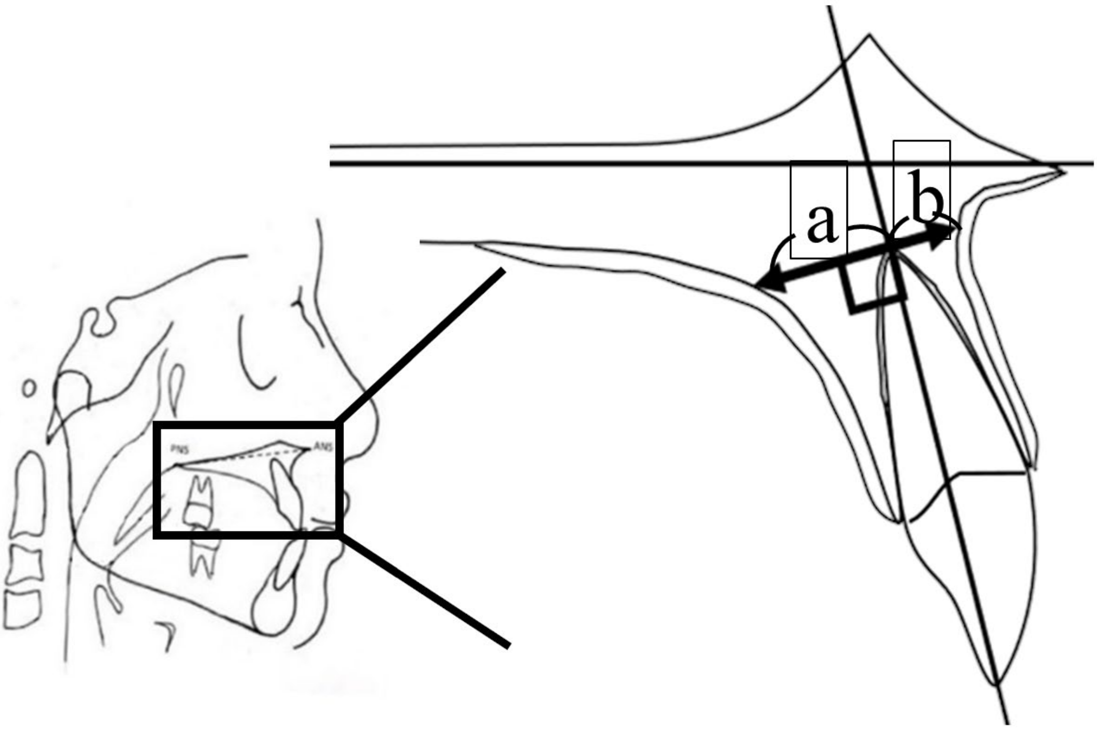


Kurasawa-Kanao et al. Fig. 2B

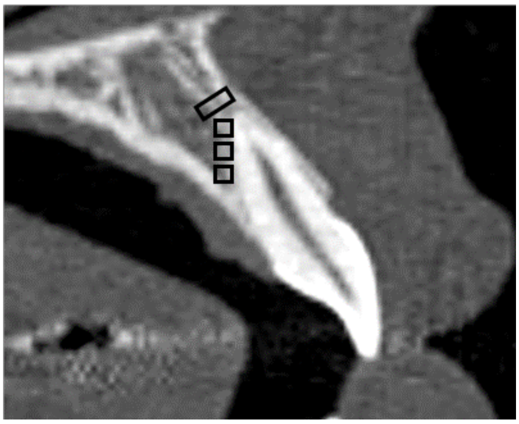


Kurasawa-Kanao et al. Fig. 3

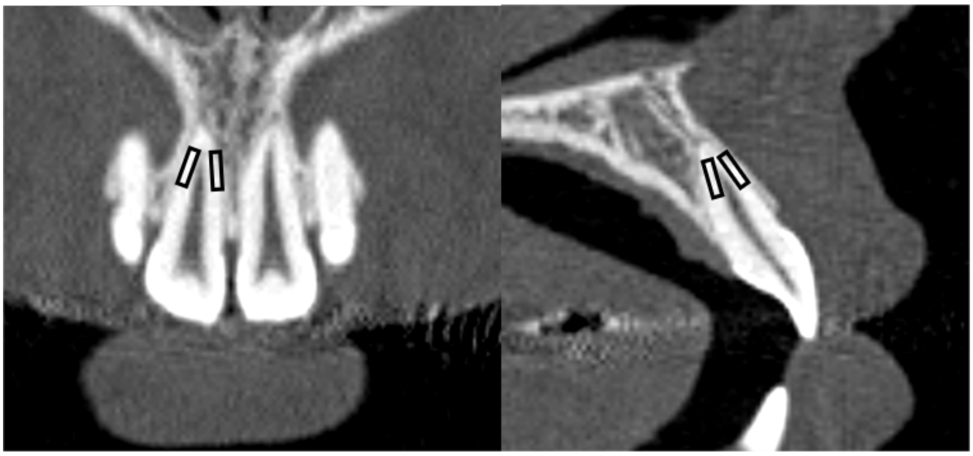
Kurasawa-Kanao et al. Fig. 4



Kurasawa-Kanao et al. Fig. 5



Kurasawa-Kanao et al. Fig. 6



Kurasawa-Kanao et al. Fig. 7

Table 1 Patient characteristics (Study 1)

	Root resorption group (n=16)	Control group (n=16)	Fisher's exact test	Welch's t-test	Mann-Whitney U test
			p-value		
Age years (±SD)	22.8 ± 6.84	22.8 ± 6.85		NA	
Sex N (percent)			NA		
male	4 (25.0)	4 (25.0)			
female	12 (75.0)	12 (75.0)			
Extraction N (percent)			0.285		
presence	11 (68.8)	7 (43.8)			
absence	5 (31.2)	9 (56.2)			
Surgery N (percent)			0.156		
1-jaw	5 (31.2)	10 (62.5)			
2-jaw	11 (68.8)	6 (37.5)			
Treatment period months (±SD)	49.6 ± 14.42	42.2 ± 10.61		0.109	
Orthodontic tooth movement					
Tooth rotation degree (±SD)	5.80 ± 5.63	8.00 ± 5.34			0.146
H_movement of root cm (±SD)	0.33 ± 0.24	0.23 ± 0.13			0.415
V_movement of root cm (±SD)	0.25 ± 0.25	0.15 ± 0.11			0.474

n: number, SD: standard deviation, NA: not applicable, H: horizontal, V: vertical

Table 2 Patient characteristics (Study 2)

	Root resorption group (n=18)	Control group (n=23)	Fisher's exact test	Welch's t-test
			p-value	
Age years (±SD)	24.0 ± 6.09	21.2 ± 3.91		0.233
Sex N (percent)			0.196	
male	4 (22.2)	10 (43.4)		
female	14 (77.8)	13 (56.6)		
Extraction N (percent)			0.752	
presence	7 (38.8)	11 (47.8)		
absence	11 (61.2)	12 (52.2)		
Surgery N (percent)			0.209	
1-jaw	6 (33.3)	13 (56.5)		
2-jaw	12 (66.7)	10 (43.5)		
Treatment period months (±SD)	46.0 ± 12.13	41.5 ± 12.22		0.296

n: number, SD: standard deviation

Table 3 Texture features of root differentiating between with and without external apical root resorption after orthodontic treatment

Texture feature	Root resorption group (n=16)	Control group (n=16)	Mann-Whitney U test	Welch's t-test	Student's t-test
			P-value		
GLRLM					
H_SRE	0.69 ± 0.09	0.80 ± 0.05		0.0006*	
H_LRE	5.04 ± 2.60	2.55 ± 0.66	0.0007*		
H_Fraction	0.59 ± 0.12	0.73 ± 0.07		0.0003*	
V_Fraction	0.54 ± 0.13	0.68 ± 0.07		0.0009*	
GLCM					
S(1,0)IDM	0.69 ± 0.11	0.56 ± 0.07			0.0005*
S(0,1) ASM	0.21 ± 0.12	0.10 ± 0.03	0.002*		
S(0,2)ASM	0.18 ± 0.10	0.09 ± 0.04	0.002*		
S(1,0) ASM	0.20 ± 0.11	0.09 ± 0.03	0.001*		
S(0,1) Entropy	0.94 ± 0.28	1.21 ± 0.14		0.002*	
S(1,0) Entropy	0.94 ± 0.26	1.21 ± 0.14		0.002*	

GLRLM: gray level run length matrix, GLCM: gray level co-occurrence matrix, SRE: short run emphasis, LRE: long run emphasis, IDM: inverse difference moment, ASM: angular second moment, H: horizontal, V: vertical, n: number

* $P < 0.01$, indicating a significant difference between the root resorption and control groups.

Table 4 Comparison of the vertical and horizontal movements of the tooth axis and root apex and the incisal edge

Variable	Group	T1 (mean ± SD)	T2 (mean ± SD)	△ (mean ± SD)	*P*-value
Inclination (θ)	Root resorption	117.29 ± 6.83	112.64 ± 6.62	-4.64 ± 7.21	0.804
	Control	118.81 ± 7.17	115.24 ± 11.58	-3.57 ± 8.37	
A-HRZ	Root resorption	42.61 ± 3.52	42.18 ± 2.51	-1.50 ± 4.02	0.032*
	Control	42.19 ± 3.01	43.25 ± 3.29	1.06 ± 2.64	
A-VRT	Root resorption	9.04 ± 2.33	8.82 ± 2.89	-0.21 ± 2.52	0.055
	Control	8.12 ± 2.25	8.94 ± 2.63	0.81 ± 1.92	
I-HRZ	Root resorption	54.61 ± 4.71	52.18 ± 3.77	-2.43 ± 4.33	0.070
	Control	54.97 ± 4.03	54.23 ± 5.17	-0.74 ± 3.37	
I-VRT	Root resorption	32.54 ± 2.55	33.11 ± 2.68	0.57 ± 2.32	0.559
	Control	30.68 ± 3.01	31.62 ± 3.45	0.96 ± 1.78	

The maxillary central incisor traces show the straight and angular measurements of the root apex and incisal edges of the maxillary central incisor. Tooth movement in the sagittal plane was measured against a perpendicular line from the posterior nasal spine. Landmarks are abbreviated as horizontal apical distance (A-HRZ), horizontal incisal distance (I-HRZ), vertical apical distance (A-VRT), and vertical incisal distance (I-VRT). Angular position (θ) is defined as the angle at which the axis of the incisor meets the palatal plane.

SD: standard deviation, △: difference between T1 and T2

Table 5 Comparison of the distance between the anatomical root apex and the incisive canal edge and cortical bone on the labial and palatal sides

Variable	Root resorption group (mean ± SD)	Control group (mean ± SD)	*P*-value
Distance between the incisive canal and maxillary central incisor (mm)	3.69 ± 1.59	3.85 ± 1.57	0.754
Distance between the labial cortical bone and maxillary central incisor (mm)	0.92 ± 0.95	1.46 ± 0.61	0.030*
Distance between the palatal cortical bone and maxillary central incisor (mm)	4.76 ± 1.87	4.57 ± 1.80	0.708

CT: computed tomography, SD: standard deviation.

* $P < 0.05$, indicating a significant difference between the root resorption and control groups.

Table 6 Comparison of CT values of the root and alveolar bone

Variable	Root resorption group (mean ± SD)	Control group (mean ± SD)	*P*-value
CT value of root (HU)	1651.343 ± 62.54	1600.39 ± 95.26	0.059
CT value of alveolar bone (HU)	760.79 ± 146.50	623.28 ± 188.06	0.015*

CT: computed tomography, HU: Hounsfield unit, SD: standard deviation.

* $P < 0.05$, indicating a significant difference between the root resorption and control groups.

Table 7 Non-standardized discriminant function

Variable	Function 1
A-HRZ	0.648*
A-VRT	0.281
I-HRZ	0.462
I-VRT	-0.174
Distance between the incisive canal and maxillary central incisor	-0.055
CT value of root	-0.367
CT value of alveolar bone	-0.578
Distance between the labial cortical bone and maxillary central incisor	0.504
Distance between the palatal cortical bone and maxillary central incisor	0.093
Inclination	-0.09

CT: computed tomography, A-HRZ: horizontal apical distance, I-HRZ: horizontal incisal distance, A-VRT: vertical apical distance, I-VRT: vertical incisal distance.

* The most relevant variable from the discriminant function.